Cascading Effects

Assessing the Performance Impacts of Fragile Tasks

ICEAA Professional Development & Training Workshop (2024)

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TECOLOTE RESEARCH

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- Methodology
  - Networking Analysis
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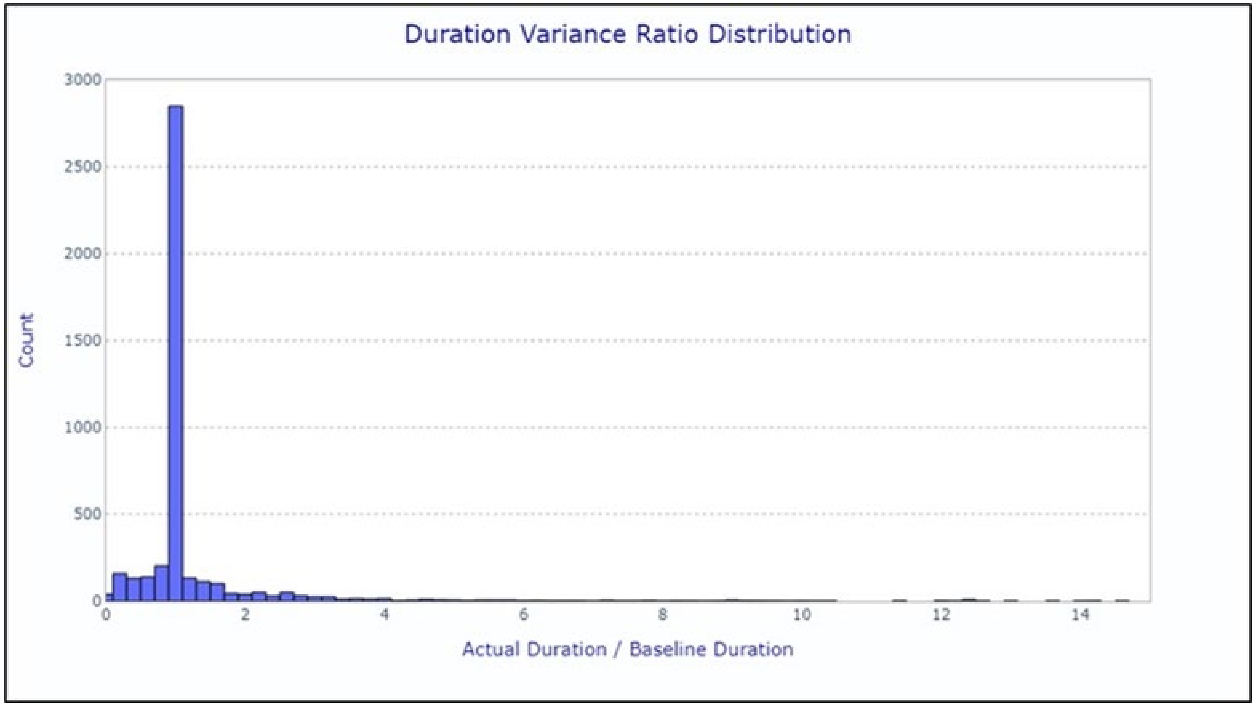
Introduction

Problem Statement

- Many tasks seem to perform well relative to their baseline. So, why do those programs consistently slip their schedule?



Background

- Example:
  - GAO reported that 98 major development acquisition programs (MDAPs) cumulatively overran their budget baseline by $402 billion and were an average of 22 months delayed in their schedules in 2010
- Potential Causes
  - Data is reported improperly and tasks are marked as being completed when, in reality, they have not
  - Optimism related to requirements and execution during baselining process and weaknesses in the BCR Process
  - Schedule Network Complexities
    - Geraldi et al. (2011) executed a systematic review of the project complexity literature
      1. Structural complexity was identified as the most significant cause of project execution issues, with large project size, task variety, and high interdependencies noted as evidence
      2. The speed of execution
      3. Misaligned incentives from organizational hierarchy
      4. Dynamic changes in personnel or system requirements

Background (cont'd)

- Current Schedule Analysis Techniques
  - Critical Path Method (CPM) uses the idea of free schedule float to estimate a delay
  - CPM treats the delay relationship between predecessors and successors linearly
  - CPM narrows the focus to a relatively small number of tasks as modern-day projects grow in complexity and does not address how project complexity impacts the critical path
- Cascading Effects of a Delay
  - Interdependencies and task uniqueness may impose nonlinear delay relationships
  - Complex networks can lead to "spreading," where localized issues on a single activity can "cascade," leading to issues with many follow-on tasks that non-linearly impacts schedule timelines
  - Schedule analysis, perhaps, need to include relationships outside CPM

Study Objectives

- Because schedule complexity can exasperate delays as they cascade through a schedule network, we need to understand if and how these patterns manifest in our MDAP program
- What tasks should leadership be most concerned with and can we identify those tasks by their potential to yield a catastrophic cascade?
  - Determine the tasks most likely to slip
  - Determine the tasks most likely to cause a catastrophic failure to the schedule

Networking Analysis Overview

- Graphs and networks are mathematical structures used to model relationships between objects, represented in the form of:
  - Nodes that are points at which connections intersect, and
  - Edges that join and connect pairs of nodes
- Many real world structures and relationships can be modeled using network analysis. Graphs provide versatile frameworks in the fields of: computer science, biology, epidemiology, social sciences, and operations research
- Node relationships types include:
  - Cycles and feedback loops (e.g. cyclic vs. acyclic)
  - Direction of property relationships among nodes (e.g. directed vs. undirected)
  - Relationship strength as measured by number of interdependencies and supporting attributes

Networking Analysis on Project Schedules

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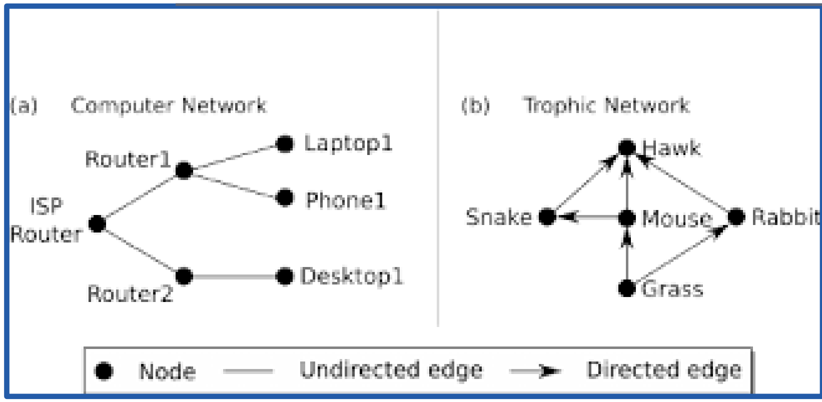
- Projects are directed, acyclic networks
  - Directed = a successor task followers a predecessor task, but not vice versa
  - Acyclic = a task is never restarted once it is completed
- Network analysis can convey project information both **Quantitatively** & **Visually**
- Centrality Measurements:
  - Provide unique insights into the value of specific nodes within the network
  - Measure task relations as, “node-level properties relating to the structural importance or prominence in the network” (Borgatti et al. 2009)
- Network diagrams can illustrate how various tasks are linked, highlighting potential bottlenecks or critical paths that may affect the project's overall timeline and budget



Computer Network as Undirected Network

- Routers and ISP hosts = nodes, enabling communication channels
- Fiber cables (strong) and WIFI (lighter) = edges, communication channels that connect the nodes together

Schedule network representations may help decision makers identify critical nodes and paths that significantly impact program health.

Networking Analysis Methodology

- Related studies (Pozzana et al. 2021 and Santolini et al. 2021): find that if schedules reflect complex networks, then “fragile” activities can lead to “spreading,” where localized issues on a single activity can “cascade,” culminating in issues with many follow-on tasks that non-linearly impacts schedule timelines
- The methodological approaches from Pozzana et al. (2021) and Santolini et al. (2021) were adopted and adapted to our MDAP program:
  - Prior research analyzed completed projects with complex networks and identified the project characteristics that cause the most significant schedule risks and issues
  - Our effort applied the same processes to completed sub-milestones of an in-progress MDAP
- Process Steps:
  1. Determine whether sub-milestones reflect complex networks
  2. Statistically measure the relationship between activity delays (e.g. deviations between actual and planned events) and key centrality measures in order verify that fragile sub-milestones lead to significant schedule delays
  3. Forecast the fragility of future sub-milestone to facilitate schedule risk assessments

1. Identifying the Complexity of MDAP Sub-Milestones

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Santolini et al. (2021) identified several measurements for network complexity:

- **Edge density**: Captures how many edges there are in a network divided by the total possible number of edges.
  - Lower Density = Sparse Density = Higher Probability of Propagating Delays
- **Number of cycles**: A cycle occurs when the network path revisits a node more than once
  - No/Few Cycles = Evidence of Directed Acyclic Graph (DAG)
- **Clustering**: Calculated as the number of closed triplets (three connected nodes) over the total number of triplets (open and closed) in a network.
  - More Clustering = Greater Complexity
- **Spreading distance**: Measures the correlation of the average schedule delay over varying distances for each task in the network.
  - Longer Spreading Distance = Greater Complexity
- **Cascade size**: Calculated as the number of downstream nodes from an initial perturbation that also experienced a start, finish, or duration delay.
  - Greater Cascade Size = Greater Complexity

2. Statistically Measure Delay and Network Relationships

- Delay Types of Interest
  - Start Delay = Baseline Start Date – Actual Start Date
  - Finish Delay = Baseline Finish Date – Actual Finish Date
  - Duration Delay = Baseline Duration – Actual Duration
- Network Centrality Measures of Interest
  - In-Degree
    - The number of nodes that directly feed into the node of interest. For schedule analytics, these are known as direct predecessors
    - A task with high in-degree has many direct predecessors, and, therefore a greater possibility of incurring a delay
  - Out-Degree
    - The number of nodes that directly follow the task of interest. For schedule analytics, these are known as direct successors
    - A task with high out-degree has many direct successors, and, therefore greater opportunity to propagate a delay
  - Reach: The number of nodes (successor tasks) reachable downstream from a given task

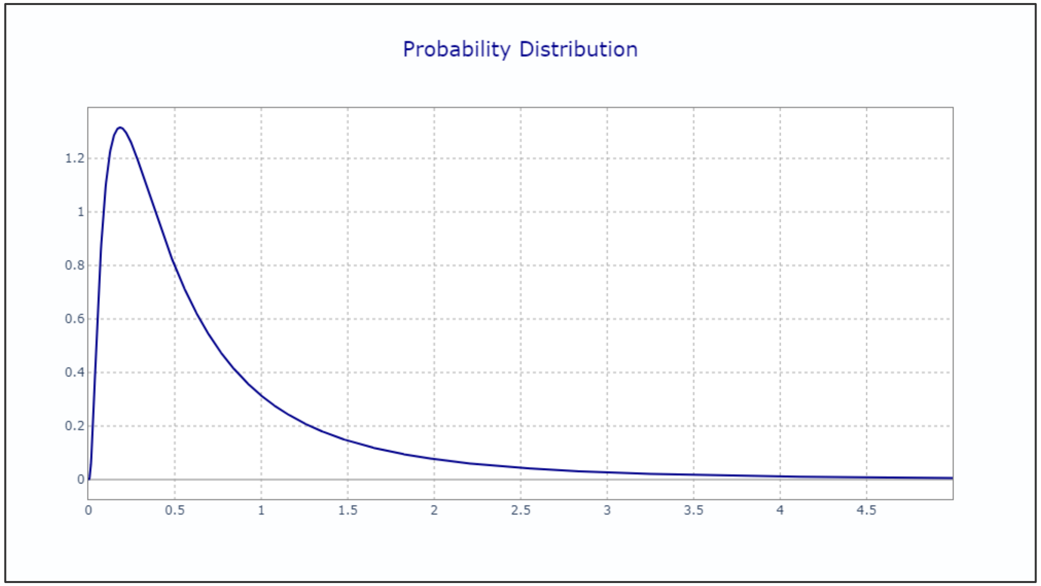
Statistical Analysis Executed using Spearman Correlations between MDAP and Null Model

3. Forecast Future Results

- Forecasting future sub-milestone schedule risk and fragility is feasible if:
  - The MDAP's completed sub-milestones are reflective of complex networks
  - A positive statistical relationship exists between sub-milestone delays and a key centrality measure (e.g. in-degree, out-degree, or reach)
  - Future sub-milestones possess comparable network complexity to completed ones
- Future high risk sub-milestones may be identified using a rank aggregation, indexing method of key centrality measures
  - Low rank scores = High schedule execution risk
- The forecasts may complement and supplement SRAs

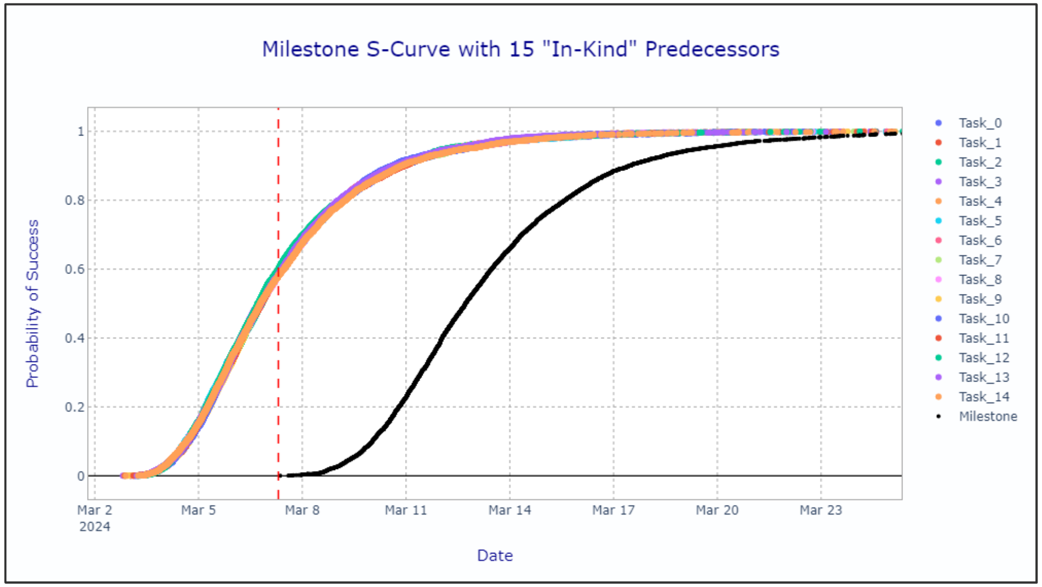
In-Degree / Merge Bias

- Answers the question: Which tasks are most likely to slip?
- Merge bias occurs when a task has high In-degree. Under certain conditions it almost certainly yields a delay
- Start with a distribution on a task duration
  - LogNormal plot looks similar to the distribution on slide 3



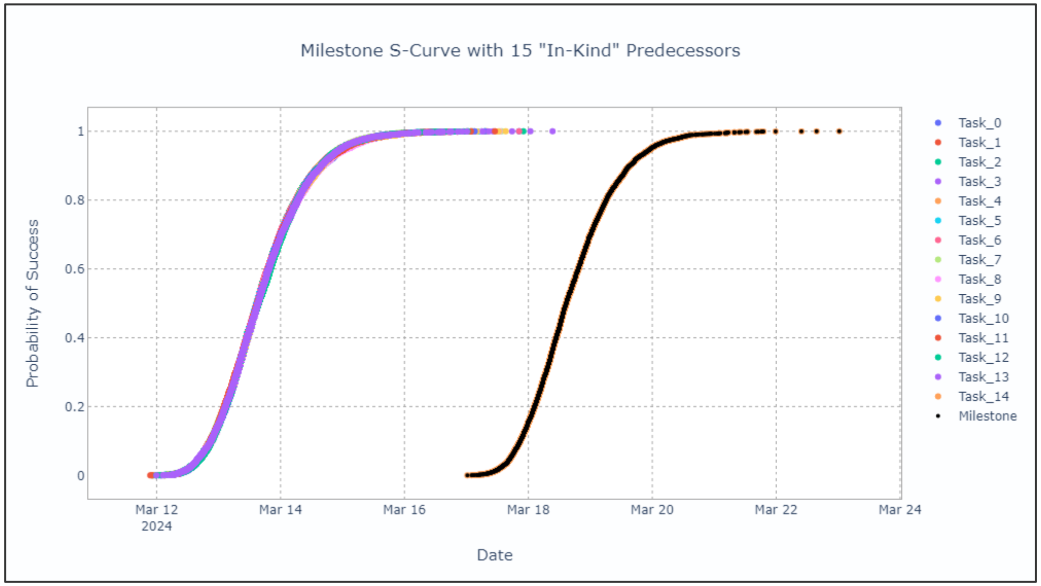
Merge Bias Analysis

- Conditions for Merge Bias:
  - Milestone occurs when all predecessors are complete (Finish-to-Start)
  - Milestone is zero-day duration
  - Predecessor tasks are baselined to end on virtually same date
  - Predecessor tasks have roughly same uncertainty distribution
  - Minimal lag between predecessors and the milestone
- Merge Bias Simulation

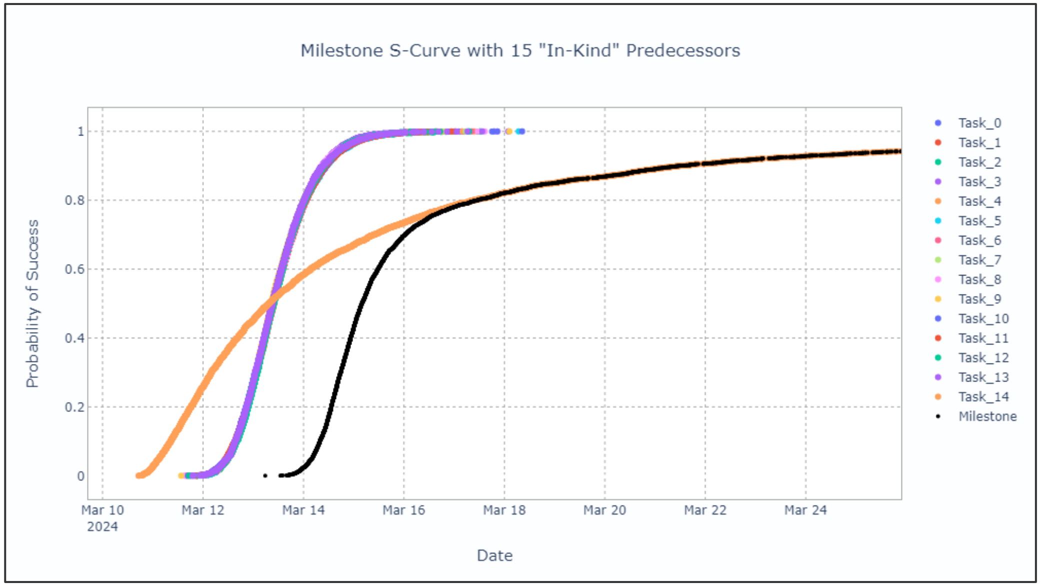


Non-Merge Bias Conditions

- One late Finish Date
  - One tasks that finishes decidedly later than the others tends to drive the milestone

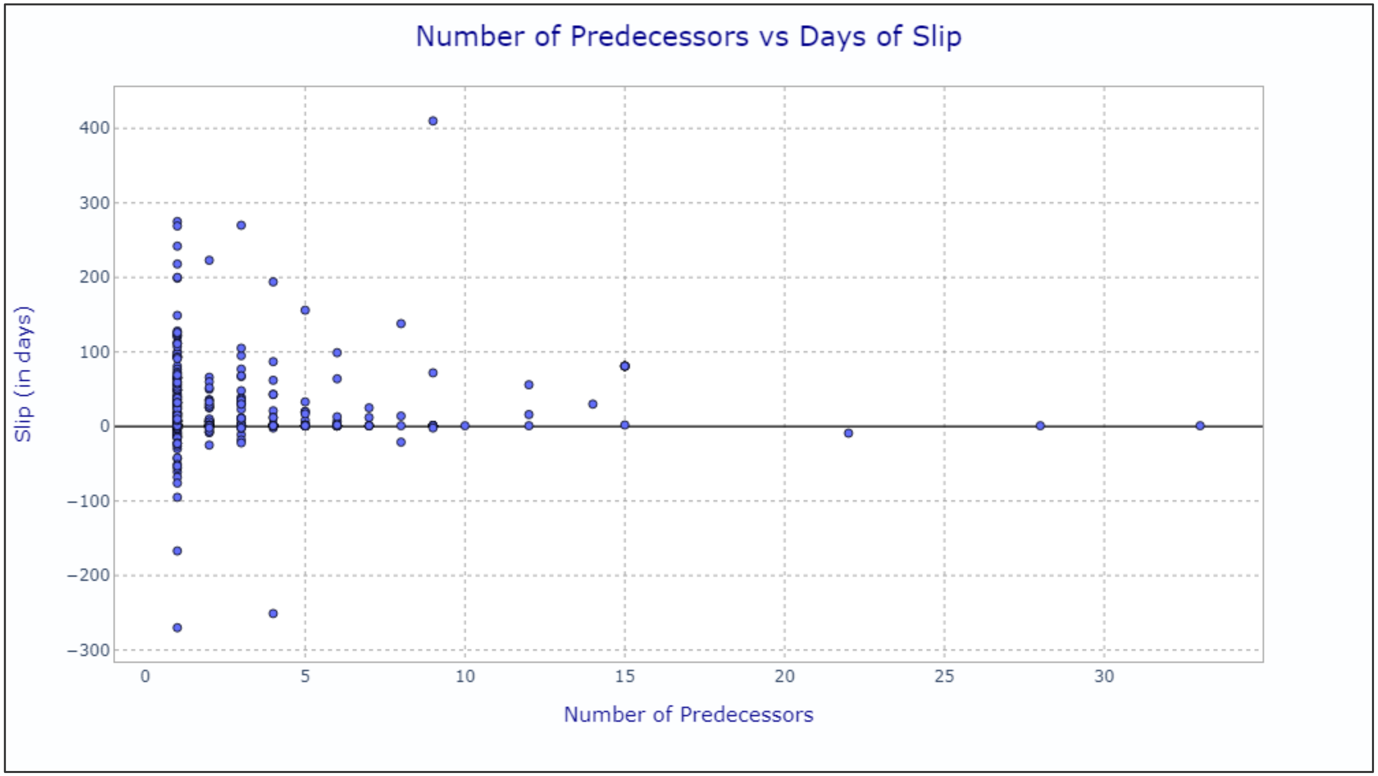


- Two: High Uncertainty
  - One task with decidedly higher uncertainty tends to drive the milestone at higher confidence levels



MDAP Program Results

- There are 397 tasks with predecessors that met the criteria for Merge Bias



Networking Analysis Execution

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- Tools:
  - SQL and Python based environments (Pandas, NumPy, igraph, etc.)
- Data: IPMDAR for our MDAP program
  - IMS > 20K tasks
  - Less than 50% of the tasks are complete
  - 12 major milestones and 13K sub-milestones
  - Study focused on 1 major milestone with approximately 5K tasks, and 2K sub-milestones
- Selection of sub-milestones to ensure network complexity
  - Removed sub-milestones with a small predecessor count (< 20)
  - Chose sub-milestones with little to no cross over tasks
  - Removed sub-milestones that did not contain clustering

1. Networking Analysis Schedule Complexity Results

Johns Hopkins Applied Physics Laboratory

- ☑ **Edge density**: Ranges between [0.003622 - 0.07381], which exhibits characteristics of a sparse network with the potential for cascading failure.
- ☑ **Number of cycles**: All sub-milestones' networks possess zero cycling, which ensures that the schedules are directed and acyclic
- ☑ **Clustering**: Our findings suggest that predecessor tasks with a schedule delay are more likely to cascade into successors
- ☑ **Spreading distance**: The sub-milestones in this study, in fact, possess a positive correlation, which indicates that delays are propagating across multiple successors in the networks
- ☑ **Cascade size**: Cascade size can be categorized by a perturbation in the Finish Dates, Start Dates, and Duration

Sub-milestones reflect directed, acyclic, complex networks, in accordance with Santolini et al. (2021)

1. Start Delay Cascading Failures

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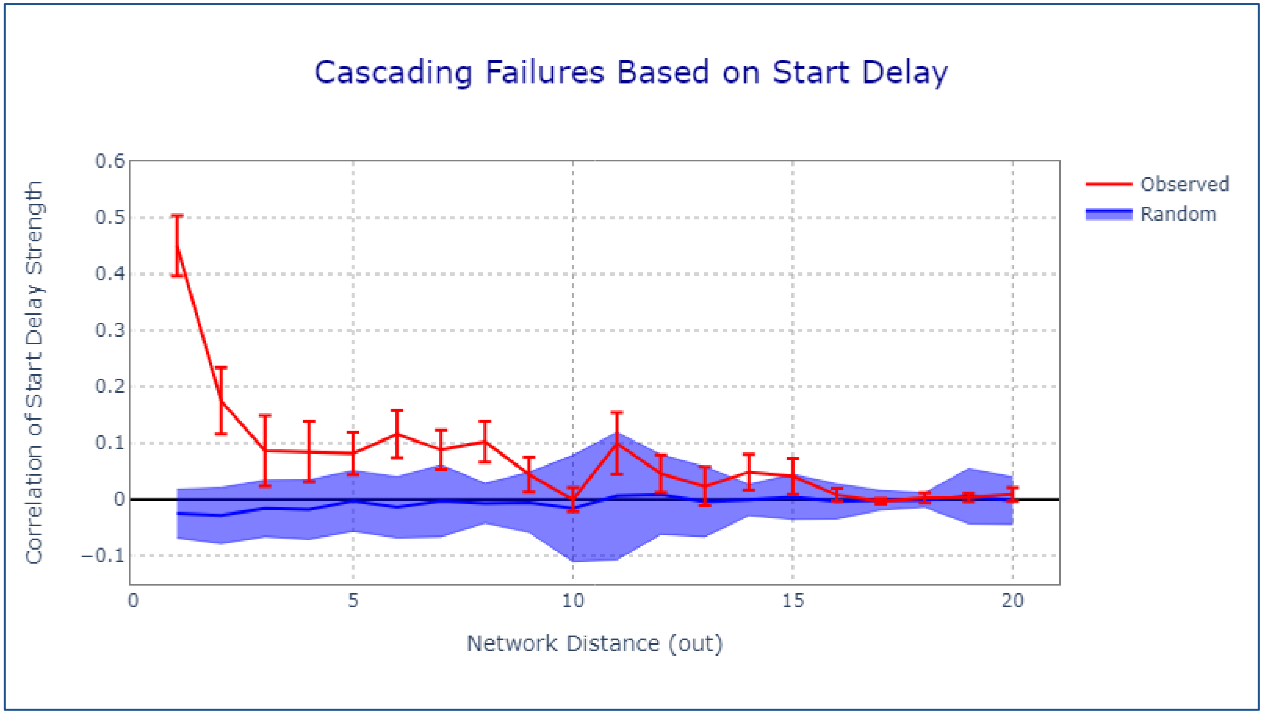
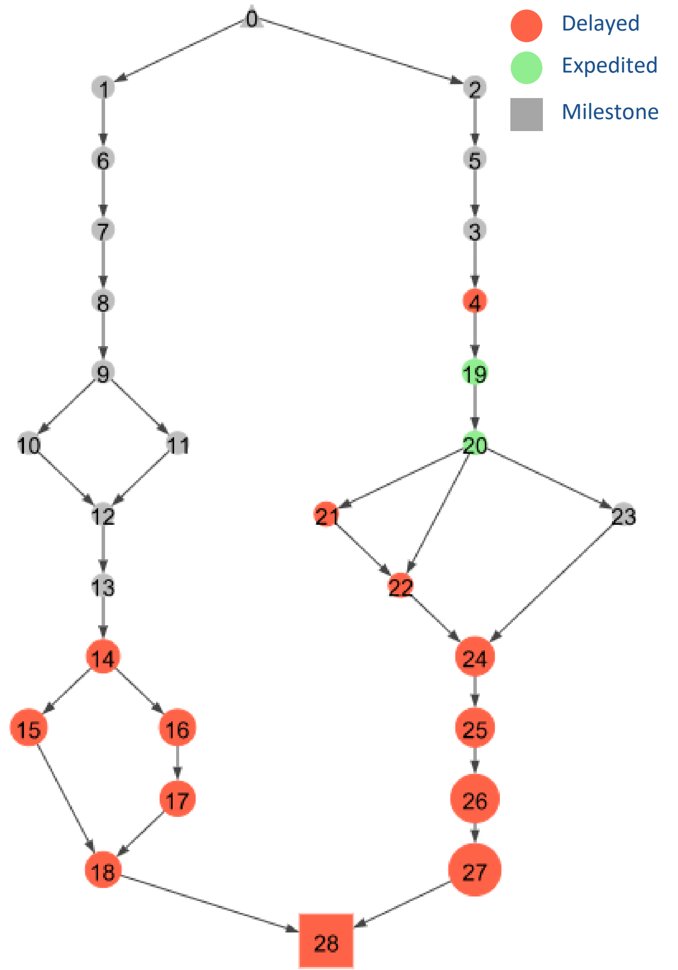
- The initial start delay of a task impacts up to 8 downstream tasks before starting to follow a randomized model





1. Finish Delay Cascading Failures

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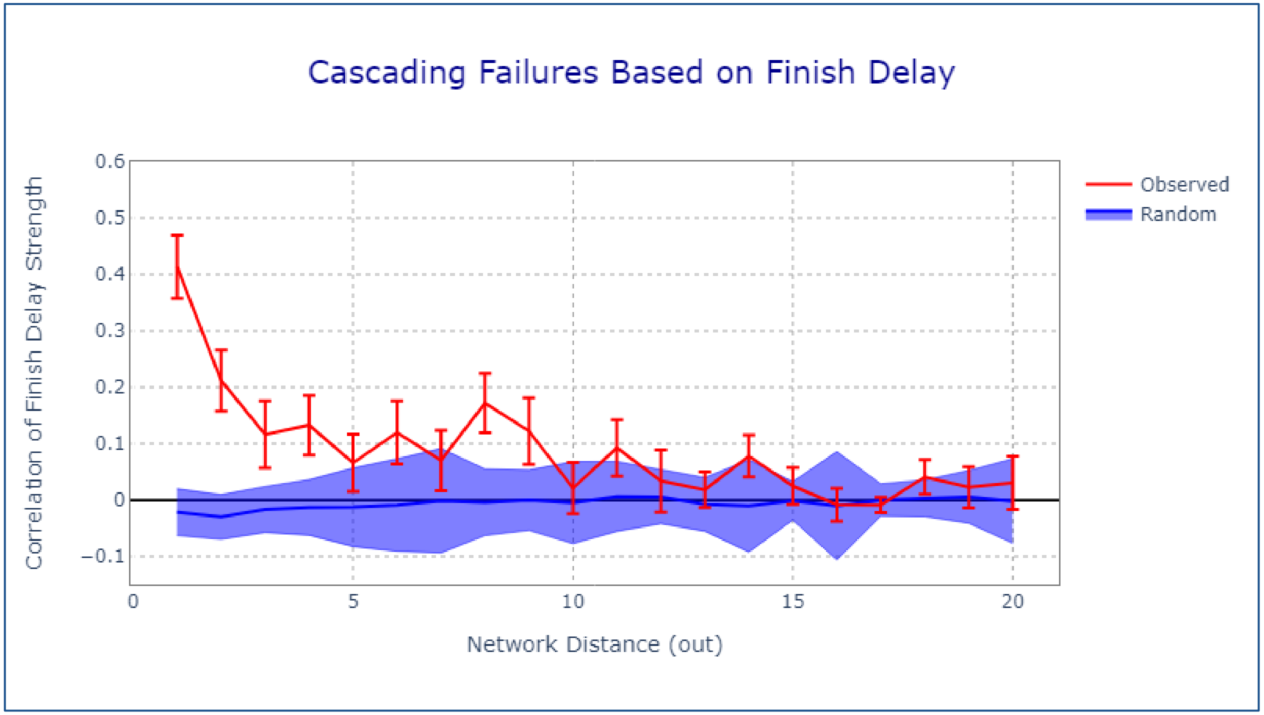
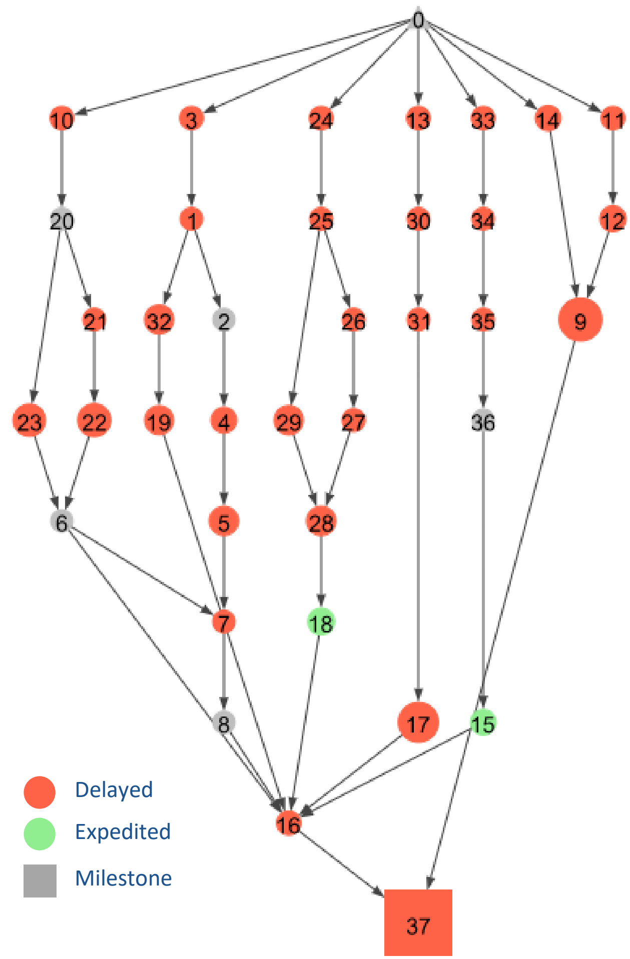
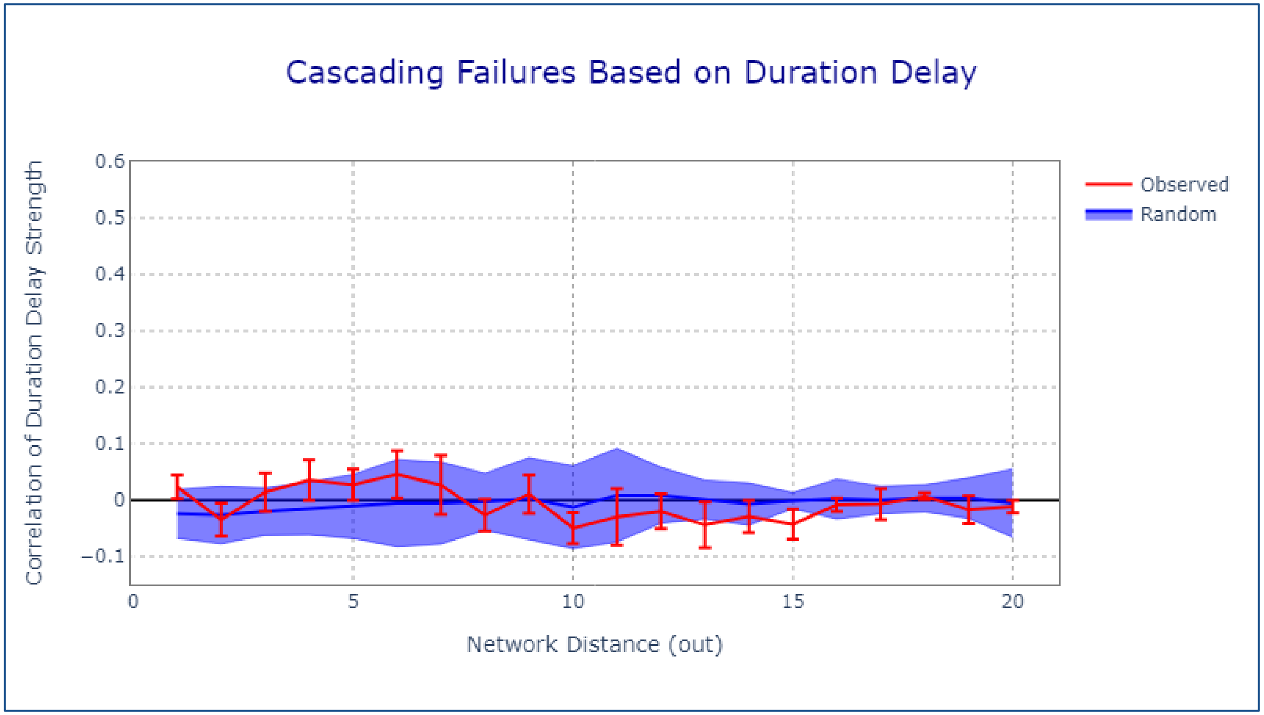
- The initial finish delay of a task impacts up to 6 downstream tasks before starting to follow a randomized model

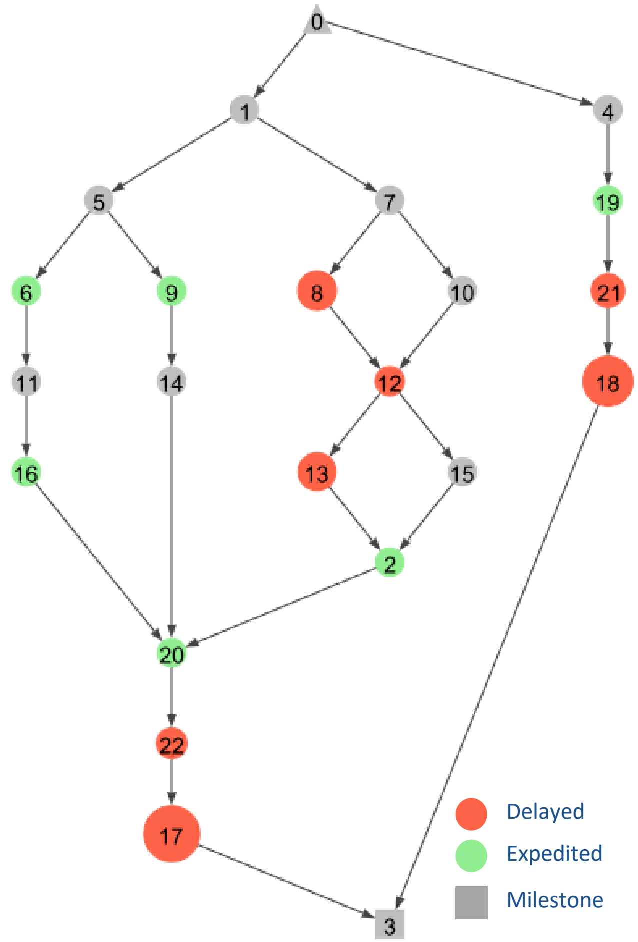




1. Duration Delay Cascading Failures

- There was no significant correlation between duration delays propagating throughout the networks

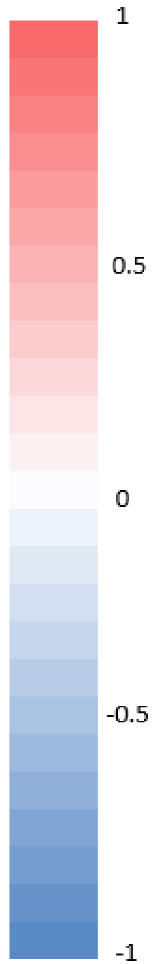




2. Centrality Metrics vs. Finish Delay Strength

Relationship Between Finish Delay Strength and Centrality Metric Sorted by Finish Delay Rate

Delay Rate	Observed				Null Model		
	reach	in-degree	out-degree		reach	in-degree	out-degree
8.6%	-0.226	0.181	0.019	Sub-Milestone 7	-0.003	-0.001	0.010
20.0%	-0.053	0.016	0.122	Sub-Milestone 19	0.016	0.009	0.036
27.6%	0.007	0.006	-0.098	Sub-Milestone 8	-0.006	0.003	0.001
37.5%	0.075	-0.094	-0.051	Sub-Milestone 10	-0.005	0.031	-0.050
40.7%	-0.360	0.026	-0.232	Sub-Milestone 16	-0.019	0.016	-0.001
45.5%	-0.264	-0.028	-0.264	Sub-Milestone 15	0.028	-0.016	0.030
47.7%	-0.294	0.082	-0.043	Sub-Milestone 18	0.009	0.009	0.003
50.0%	-0.279	-0.161	-0.092	Sub-Milestone 25	0.031	-0.005	-0.004
50.0%	-0.348	-0.067	-0.039	Sub-Milestone 20	0.008	0.006	0.012
54.5%	-0.149	0.181	-0.021	Sub-Milestone 5	0.003	0.006	0.004
57.7%	-0.373	0.042	-0.563	Sub-Milestone 13	-0.002	-0.011	0.005
58.8%	-0.452	0.201	-0.120	Sub-Milestone 1	0.043	-0.010	-0.002
60.0%	-0.543	0.219	-0.141	Sub-Milestone 23	-0.006	-0.016	-0.017
60.3%	-0.503	-0.133	-0.319	Sub-Milestone 3	-0.001	0.017	-0.005
60.8%	-0.233	-0.082	-0.250	Sub-Milestone 2	-0.019	0.010	-0.016
61.9%	-0.701	0.288	-0.231	Sub-Milestone 17	0.024	0.008	-0.014
62.1%	-0.456	-0.016	-0.327	Sub-Milestone 4	0.000	-0.032	0.000
63.3%	-0.187	0.114	-0.328	Sub-Milestone 22	-0.005	0.011	-0.020
66.7%	-0.143	0.335	-0.445	Sub-Milestone 12	-0.010	0.014	-0.049
72.0%	-0.549	0.096	-0.338	Sub-Milestone 9	0.010	-0.008	0.049
78.4%	-0.388	0.145	-0.504	Sub-Milestone 21	0.017	0.044	-0.014
78.6%	-0.709	0.202	-0.202	Sub-Milestone 11	-0.001	0.004	0.005
78.6%	-0.542	0.272	-0.220	Sub-Milestone 24	-0.041	0.013	-0.021
83.3%	-0.763	0.376	-0.081	Sub-Milestone 6	0.012	0.001	0.008
95.2%	-0.683	0.530	-0.124	Sub-Milestone 14	0.019	-0.043	-0.003



3. Future Sub-Milestone Fragility

- The network analysis is ultimately used to forecast schedule risk given the positive and increasing correlation between degree and finish delay
- The study team calculated centrality measures for future sub-milestones that were in the 18-month planning time horizon

Name	Contractor Critical	WBS ID	Aggregate Rank	In-Degree Rank	Out-Degree Rank
Future Sub-Milestone 11	True	1.02.XX.XX.XX.XX	1	1	1
Future Sub-Milestone 2	True	1.02.XX.XX.XX	4	2	6
Future Sub-Milestone 16	True	1.02.XX.XX.XX	6.5	6	7
Future Sub-Milestone 10	True	1.02.XX.XX.XX	9	4	14
Future Sub-Milestone 14	True	1.04.XX.XX.XX.XX	18.5	33	4
Future Sub-Milestone 7	False	1.02.XX.XX.XX.XX.XX	28	28	28
Future Sub-Milestone 4	True	1.02.XX.XX.XX	29.5	11	48
Future Sub-Milestone 3	True	1.02.XX.XX.XX	30	13	47
Future Sub-Milestone 9	True	1.02.XX.XX.XX	34.5	20	49
Future Sub-Milestone 12	True	1.04.XX.XX.XX.XX	39	45	33
Future Sub-Milestone 5	True	1.02.XX.XX.XX.XX.XX	40	53	27
Future Sub-Milestone 6	False	1.02.XX.XX.XX	40.5	7	74
Future Sub-Milestone 15	True	1.08.XX.XX.XX.XX	42	17	67
Future Sub-Milestone 13	True	1.02.XX.XX.XX.XX.XX	42	79	5
Future Sub-Milestone 17	True	1.02.XX.XX.XX	45	18	72
Future Sub-Milestone 1	True	1.07.XX.XX.XX.XX.XX	47.5	22	73
Future Sub-Milestone 8	True	1.02.XX.XX.XX.XX.XX	47.5	78	17

Conclusion

- Study team encountered several limitations, specifically limited data from which to conduct the analysis
- The analysis should be beneficial to the community
  - Applies emergent research on project schedule networking analysis to a real IMS for a DoD MDAP
  - Replicates some of the existing research hypotheses (Santolini et al. 2021), specifically the importance of node degree on task delays
    - Corroborates current project schedule postulates regarding merge biases
    - Tasks with a greater in-degree are leading to cascading failures for the completed portions of this MDAP's IMS
- The incorporation of both standard and adapted centrality measurements that correlate with schedule fragility may be readily used to investigate high cascade probability tasks on other MDAPs